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A Herschel Spectroscopic Survey of Warm Molecular Gas in Local Luminous Infrared Galaxies

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Abstract. We describe an on-going *Herschel* 200-700 μm spectroscopic survey of a flux-limited sample of 125 local luminous infrared galaxies (LIRGs), targeting primarily at CO line emission from warm and dense molecular gas. The program will provide important statistical data on the interplay between warm molecular gas, IR luminosity, star formation rate and efficiency, AGN, and the diverse properties of LIRGs. Of the 30 sample galaxies observed so far (18 by us; 12 taken from *Herschel* archive), about 15% show a dominant or significant hot CO gas component emitting at $J > 10$, that is likely heated by AGN. The other 85% is dominated by a warm gas component with CO line emission peaking at $J \lesssim 8$, likely powered by starburst. While the spectral shapes of the warm gas component show little overall dependence on the total IR luminosity L_{IR}, the relative contribution from the hot component appears to correlate positively with L_{IR}. The tightest one-to-one correlation between CO line luminosity and L_{IR} seems to be for CO(7-6), implying that the bulk of L_{IR} should be correlated with warm molecular gas of such density and temperature that its CO line emission peaks around $J \sim 7$.

1. Introduction

We have started a campaign to obtain 200-700 μm spectra for an IR flux-limited sample of 125 local luminous infrared galaxies (LIRGs: with an 8-1000 μm $L_{IR} > 10^{11} L_{\odot}$) with the SPIRE Fourier Transform Spectrometer (FTS) on board *Herschel* (Pilbratt et al. 2010), with the main goal of obtaining CO spectral line energy distribution (SLED) to beyond mid J levels to probe warm and dense molecular gas that should be more directly related to star formation rate than cold molecular gas traced by CO(1-0) (e.g., Iono et al. 2009). Unlike ultra-LIRGs (ULIRGs; $L_{IR} > 10^{12} L_{\odot}$), which are almost exclusively found in merging systems of two gas-rich disk galaxies (Sanders & Mirabel 1996), LIRGs form a morphological diverse group of galaxies, ranging from close galaxy-galaxy interactions, to widely separated pairs, and to relatively isolated spirals. Contrary to other *Herschel* programs, ours puts an emphasis on typical nearby luminous LIRGs to obtain a more complete understanding of molecular gas properties, star formation activity and AGN phenomenon in LIRGs.

2. The Program

As Fig. 1 shows, our sample is a subset of the one used in the Great Observatories All-Sky LIRGs Survey (GOALS; Armus et al. 2009), which is complete to a flux density of 5.24 Jy at 60 μm, and consists of all the 125 GOALS individual galaxies with $L_{IR} > 10^{11} L_{\odot}$ and a total IR flux $F_{IR} > 6.5 \times 10^{-13}\,\mathrm{W\,m^{-2}}$. Our own observations cover 93 galaxies with the remaining 32 having similar FTS spectra from existing *Herschel* programs.

In order to cover a large sample, our observations use the staring mode and an integration time to detect CO(6-5) at S/N > 5. The total telescope time per target ranges from 1,764 to 8,524 seconds, depending on the anticipated CO(6-5) fluxes. Since the SPIRE FTS sensitivity is more or less flat for higher J CO lines, this design still allows us to have some confidence in differentiating a flat-to-rising SLED, which calls for a strong gas heating by AGN (e.g., Mrk 231; van der Werf et al. 2010), from a declining one beyond $J \sim 7$, which indicates a starburst dominated galaxy nucleus (e.g., M 82; Panuzzo et al. 2010).

At the time of this report, eighteen targets have been observed by us. These data, together with additional 12 sample galaxies with public FTS data from *Herschel* data archive, are used here. The data reduction was done in a homogeneous way, using *Herschel* HIPE version 7. For the majority of the galaxies considered here, their warm CO emission should resemble a point source for the SPIRE beams. Therefore, each galaxy spectrum is simply taken from the central SPIRE detectors (i.e., SSWD4 & SLWC3). As an example, Fig. 2 shows the spectrum of a relatively faint galaxy, NGC 0695. In almost every case, clearly detected lines are CO lines up to some J level, one or both of the [CI] lines at 369 and 609 μm, respectively, and the [NII] 205μm line. Our detected CO lines are mostly unresolved. We have fit the spectral lines into SINC profiles and the underlying continuum into a polynomial. The SINC line profile fitting is quite satisfactory, except for the [NII] line, which may be partially resolved in some cases. In the remainder of this report, we present some first results based on the detected CO lines, referring to a formal paper (Lu et al. 2012; in preparation) for details on the sample, observations and a full data reduction and spectral analysis.

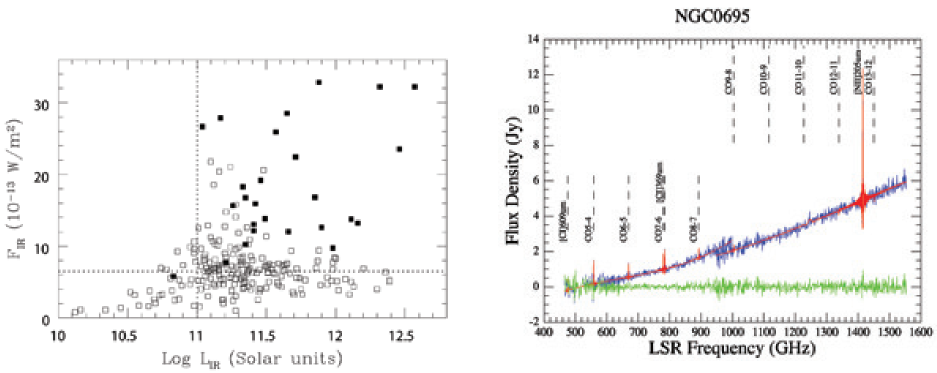

Figure 1. Left. Plot of the total IR flux as a function of the total IR luminosity for all the individual galaxies (including some minor galaxy pair members) in the GOALS sample. The two dotted lines indicate our sample selection as described in the text. The filled squares are 32 galaxies observed in other SPIRE FTS programs. Right. The observed spectrum of NGC 0695 (in blue) and an illustration of line and continuum fits (in red). The relative flat spectrum (in green) is the residual after the fits. Also marked are potential CO lnes, the two [CI] lines and the [NII] 205μm line. In this case, CO lines up to J=8-7 are clearly detected.

3. First Results

As examples, we show in Fig. 3 the observed CO SLEDs for two relatively IR compact galaxies, NGC 0695 and CGCG 436-030. These plots are constructed using detected CO lines at $S/N > 3$, where the line flux uncertainty N is based on a simple r.m.s. value (including any fringes) measured in the residual spectrum. NGC 0695 is a starburst with an IRAS color of $f_\nu(60)/f_\nu(100) = 0.55$. By contrast, CGCG 436-030 may harbor a LINER and has a blue *IRAS* color of 1.11, which may be correlated with its flatter CO SLED. Of the 30 galaxies studied here, about 15% (4 galaxies) of the sample galaxies have a SLED that clearly peaks beyond $J = 8$. The other 85% (26 galaxies) have their SLEDs peaking at $J \leq 8$. The 4 galaxies in the former group are all known AGNs. But not all the known AGNs fall into this group. The SPIRE FTS sensitivity ensures that none detections of CO lines at $J > 8$ correspond to a declining CO SLED above that J level. Since an AGN related X-ray gas heating produces a CO SLED that peaks well beyond $J = 8$, a reasonable conclusion from this statistical result is that X-ray gas heating is not the *dominant* mechanism in the majority of LIRGs.

Fig. 3 shows a few plots of the line flux ratio of CO(J-[J-1])/CO(5-4) as a function of L_{IR}, for J between 6 and 12. Up to $J \sim 8$, the ratios show little overall dependence on L_{IR} for $L_{IR} < 10^{12} L_\odot$. By contrast, at $J \gtrsim 11$, there appears to be a clear trend over the entire luminosity range. A plausible, simplified model for this consists of two CO gas components: a warm component that dominates mid-J CO lines and a hot component that dominates high-J CO lines. The latter component becomes progressively important as L_{IR} increases, to the point that its significance is noticeable for the 3 ULIRGs in all the plots in Fig. 4.

We show luminosity correlations between various CO lines and L_{IR} in Fig. 5. In producing these plots, we have applied a *crude* aperture correction to each CO line luminosity using the fraction of *Spitzer* 24 μm flux within a fixed aperture comparable

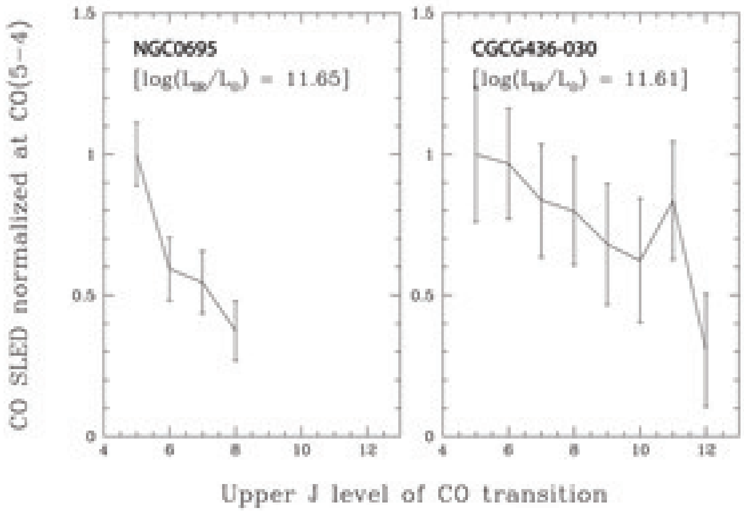

Figure 2. CO SLEDs, normalized at CO(5-4), for two sample galaxies of comparable L_{IR}.

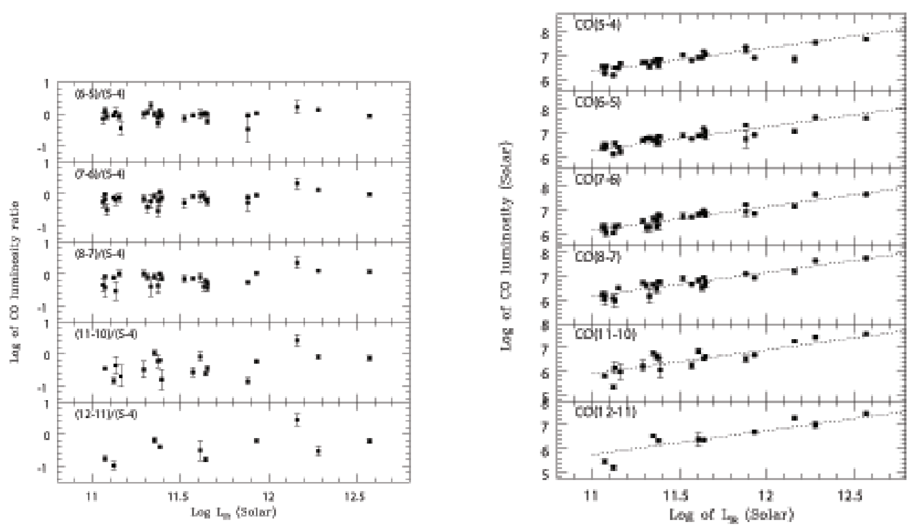

Figure 3. Left. Plots of CO line ratios as a function of the IR luminosity. The J levels of the CO lines used in the ratio are labelled in each plot. Right. Plots of selected CO line luminosity as a function of the total IR luminosity. In each plot, the dotted line is a best fit to the data at a fixed slope of unity.

to the largest SPIRE FTS beam (42″ FWHM). Except for a few cases, this correction factor is less than 15%. The dotted line in each plot is a best fit to the data points with a fixed slope of unity. The best overall fit seems to be around $J = 7$. For $J < 6$, the data distribution seems to be slightly shallower than the fit. By contrast, at $J = 12$, the opposite seems to be true. These plots imply that L_{IR} is mostly associated with warm molecular gas of such density and temperature that the CO line emissions peak around

$J \sim 7$. This analysis needs to be repeated with more galaxies and a more rigorous treatment of the aperture correction and calibration errors.

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